3.2. SOLAR AND THERMAL ATMOSPHERIC RADIATION

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3.2.1. RADIATION MEASUREMENTS

Introduction

The CMDL Solar and Thermal Atmospheric Radiation (STAR) project provides supporting information for baseline climate monitoring activities and investigates trends and variations in the observed surface radiation budget. Energy associated with the Earth's radiation budget is not only responsible for maintaining the thermal state of the planet but also causes atmospheric and oceanic motions. Expected trends in surface radiation quantities at globally remote sites caused by anthropogenic activities are near or below the level of detectability, on the decadal time scale. However, there are gaps in the knowledge of basic climatological variability in the global surface radiation budget such that STAR measurements can contribute to a fundamental understanding of atmospheric and climatological processes. These contributions include definition of diurnal and annual cycles and effects of cloudiness, actual variation on daily to decadal time scales, major volcanic eruptions, unexpectedly high concentrations of anthropogenic pollution in the Arctic, constituent variations on narrowband irradiance (e.g., ozone and ultraviolet (UV) changes), and possible anthropogenic modification to cloudiness. The STAR group also makes remote sensing measurements of various atmospheric constituents that are potentially responsible for variations in surface radiation quantities, particularly aerosol optical depth. In addition to the research conducted by CMDL and the locally maintained data archives, STAR measurements contribute to several global databases. Databases that are global in extent are needed to evaluate radiation and energy budgets in diagnoses of the climate. STAR observations also contribute to satellite-based projects by helping verify point estimates and thereby allowing intervening features of the atmosphere to be deduced.

A major goal of the monitoring program is to obtain a record of surface radiation parameters that is as long and complete as possible and that can be examined for all scales of natural and modified variability. Of particular interest is the determination of the magnitude, representativeness, and possible consequences of any observed changes. To this end, the STAR group maintains continuous surface radiation budget observations at several globally diverse sites, along with various ancillary observations. The following describes those projects and changes since the previous *CMDL Summary Report* [*Schnell et al.*, 2001].

Baseline Monitoring Sites

Surface radiation measurements have been made at the four principal CMDL baseline observatories (BRW, MLO, SMO, and SPO) since the mid-1970s, with some measurement series going back to 1957. The different environments and observing conditions at the sites resulted in somewhat different measurement programs evolving at each site. The basic measurements made at all sites include the downward components of solar radiation: global, diffuse, and direct. Broadband thermal infrared (IR) irradiance measurements were added over the past 15 years. Upward solar and thermal IR are measured at sites where the surrounding terrain is representative of a larger regional area, such as at SPO and BRW, for at least part of the year. The records acquired at these sites constitute some of the longest known series available by the United States for solar radiation research. The raw data are routinely transmitted from the field sites over telephone lines or the Internet to the central data processing facility in Boulder, where data editing, final calibrations, graphical inspection, and archiving are performed, as discussed in section 3.2.9.

Other Measurement Sites

Boulder Atmospheric Observatory (BAO Tower). Observations of upwelling and downwelling solar and thermal irradiances began in 1985 at the top of a 300-m-tall tower, known as the Boulder Atmospheric Observatory (BAO), which is located near Erie, Colorado. Nearly continuous observations of these quantities were made with hourly resolution until 1992, 3-min resolution until 1998, and 1-min resolution thereafter. The upwelling data provide a unique view of surrounding agricultural land, making the data more representative than typical surface-based solar radiation budget observations. This site has contributed data to the World Climate Research Program (WCRP) Baseline Surface Radiation Network (BSRN). Applications of data from this site were described in the 1998-1999, and earlier, *CMDL Summary Report*s [e.g., *Schnell et al.*, 2001]. Since 1990, observations of direct solar and downwelling solar irradiances have also been made near the base of the tower. Measurements of aerosol optical depth were added in the past 2 years, as were observations of the direct solar beam with an all-weather absolute cavity radiometer.

Kwajalein. Observations of direct solar and downwelling solar and thermal IR irradiance began on Kwajalein in 1989. Kwajalein is a small, <4-km^2, island in the tropical western Pacific. Data obtained at this location are virtually free of any effects of the island and therefore are often taken as representative of the open ocean in that region. Data from Kwajalein have been used as oceanic representative by *Dutton* [1993], *Whitlock et al.* [1995], and *Bishop et al.* [1997], and are currently being used by the Cloud and Earth's Radiant Energy System (CERES) and the European Centre for Medium-Range Weather Forecasts (ECMWF) global circulation model (GCM). Substantial upgrades to the Kwajalein radiation measurements were carried out in the past 2 years because a corrosive marine environment requires that much attention be given to the instrumentation. The Kwajalein site is a participant in the BSRN program and receives much of its funding from the National Aeronautics and Space Administration (NASA), which has a large interest in CMDL's radiation mea-surement activities in general.

The installation of a new permanent stairway to the Kwajalein measurement platform was completed, new tables for sensors and the solar tracker were constructed, and all equipment was relocated during August 2000.

Bermuda. Observations of downwelling solar and thermal IR began at the NASA Tracking Station at the east end of Bermuda in 1990. The rather small size and low relief of this island, located in the lower midlatitude westerlies, has minimal influence on the irradiance measurements, although some clouds of orographic origin are known to exist there in the summer months under certain synoptic meteorological conditions. Data from Bermuda have been submitted to the BSRN data archive and were used by *Whitlock et al.* [1995] and *Bishop et al.* [1997], and currently by the CERES program in satellite comparison and validation studies and by ECMWF and Geophysical Fluid Dynamics Laboratory (GFDL) in their GCM testing. The monitoring site was moved in 1998 from the NASA Tracking Station (32.2670ºN, 64.6670ºW) near the east end of the island to the top of Prospect Hill near the center of the island (32.3009ºN, 64.7659ºW). The site is ably tended by the Bermuda Biological Station for Research and is also funded largely by NASA.

Basic Measurements

Broadband irradiance. The basic broadband measurements currently conducted at each of the four baseline observatories for the past 26 years include normal direct and downward broadband solar irradiance and downward solar irradiance in the 0.28-µm to 2.8-µm band. Downward broadband thermal irradiance measurements were added at all sites in more recent years as well as upwelling irradiance measurements at SPO and BRW. The current suite of measurements at all sites is shown in Table 3.7. Data are sampled at 1 Hz with 1-min averages recorded on computer media. Preliminary data from all CMDL radiation sites are generally available, graphically, within a couple of days of acquisition in the Radiation section of the CMDL web site, and subsequently as described in section 3.2.9. The *CMDL Summary Report* for 1998-1999 [*Schnell et al.*, 2001; page 59] shows different example summaries of the 24-yr record of total solar irradiance collected at SMO using the single pyranometer technique.

Filter wheel NIP. The wideband spectral direct solar irradiance measurements are made with a filter wheel normal incidence pyrheliometer (FWNIP). One of the applications of these data is to compare them with a high-spectral-resolution radiative transfer model [*Bird and Riordan*, 1986] that is based on Beer's law and is intended for use at the surface only. The aerosol optical depth and precipitable water are adjusted within the model to obtain the best match with the FWNIP observations. This provides a low-precision but relatively stable estimate of mean visible aerosol optical depth and water vapor at the four baseline observatories. The accuracy of the method for obtaining aerosol optical depth and water vapor is limited by the dependence on the absolute values of the extra-terrestrial solar spectrum and instrument calibration, unlike other typical applications in sunphotometry. The updated data records from these observations are shown in Figure **3.15** through near the end of 2001. The accuracy of the data is on the order of 0.03 optical depth units, or about 2 to 3 times poorer than sunphotometer-derived values and should only be used when sunphotometer-derived data are not available.

MLO apparent transmission. The transmission for direct broadband solar irradiance through the atmosphere above MLO is monitored as a quantity known as the apparent

TABLE 3.7. Measurement Types Made at Each Station, 2000-2001

	BRW	Bermuda	BAO	MLO	Kwajalein	SMO	SPO
Broadband Irradiance (until otherwise noted)							
Direct solar beam	X	X	X	X	X	X	X
Diffuse solar	X	X	X	X	X	X	X
Total downward solar	X	X	X	X	X	X	X
Reflected solar	X		X				X
Downward IR	X	X	X	X	X	X	X
Upward IR	X		X				X
Other Measurements							
Spectral optical depth	X	X	X	X	X		X
All-sky digital imagery	X		X				
UV-B	X	X	X	X	X		
High-resolution spectral UV			X*	X			
Wideband direct solar irradiance (FWNIP)	X			X		X	X

BRW, Barrow, Alaska; BAO, Boulder Atmospheric Observatory (Erie, Colorado); MLO, Mauna Loa, Hawaii; SMO, American Samoa; SPO, South Pole, Antarctica.

*Instrument located in Boulder about 16 km west of BAO.

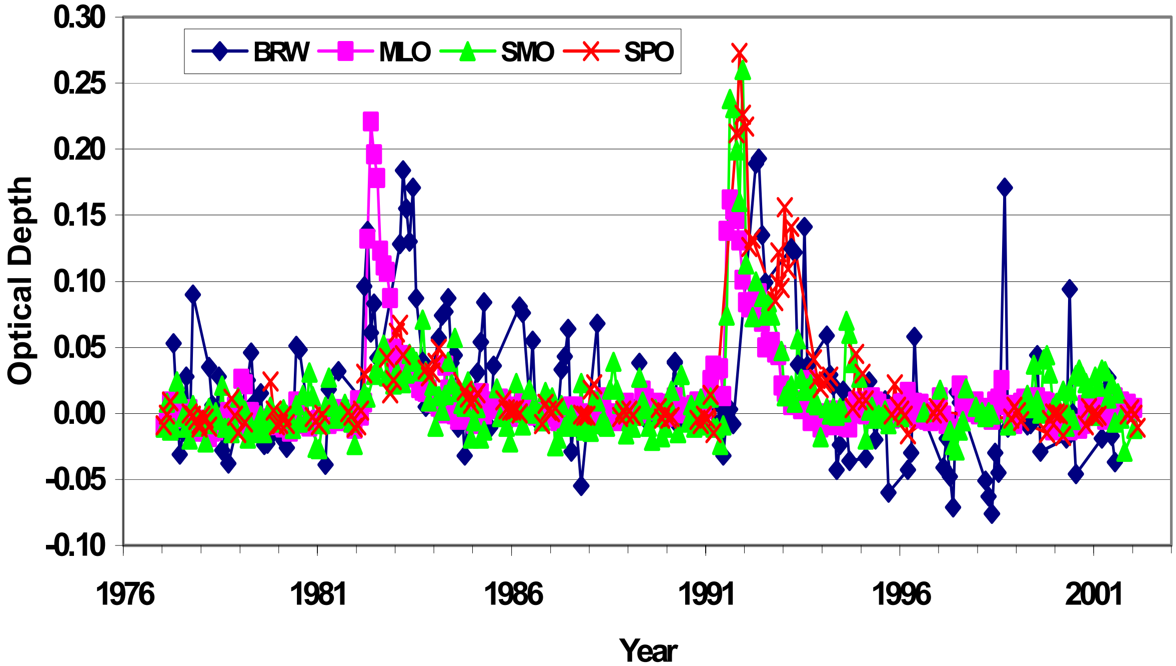

Fig. 3.15. Aerosol optical depth anomalies, monthly averages from wideband filter wheel NIP estimates.

transmission. This quantity is computed as the average of three successive ratios of direct solar irradiance, where each ratio is the quotient of the irradiance at an integer airmass divided by the irradiance at the next smaller integer airmass, as first defined by *Ellis and Pueschel* [1971]. The apparent transmission measurement is inherently stable over time because it is independent of a radiometer calibration value and is therefore also quite sensitive to small changes in transmission that can be due to aerosols, ozone, or water vapor.

Studies by *Bodhaine et al.* [1981] and *Dutton et al.* [1985] have shown that aerosols tend to dominate observed changes in the monthly averages of apparent transmission such that the major observed excursions in the record, shown in Figure 3.16, are due to aerosols. The major observable features in Figure 3.16 are the effects of several volcanoes, particularly Agung in 1963, El Chichón in 1982, and Pinatubo in 1991, and an annual oscillation caused primarily by the springtime transport of Asian dust aerosol over the site [*Bodhaine et al.*, 1981]. Figure 3.16 is complete through 2001 and shows that the recovery from the eruption of Mt. Pinatubo required several years. The fact that the Mauna Loa apparent transmission record took several years to recover from Pinatubo is evidence of the sensitivity of the measurement, because it is known from other measurements by CMDL and others that the optical depth of Pinatubo in 1995 was already very low, on the order of 0.005 at 500 nm. *Dutton and Bodhaine* [2001] have used the MLO transmission record to deduce the maximum possible change in certain solar radiation budget quantities that could have occurred over the length of the

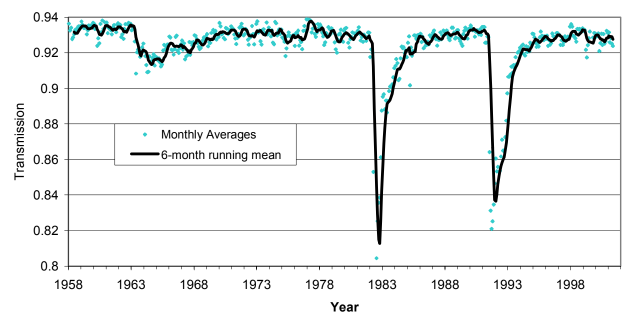

Fig. 3.16. Apparent solar transmission observed at Mauna Loa.

record. The long-term atmospheric transmission was converted to net solar irradiance at MLO by comparison to more recent accurate measurements of surface irradiance, and assumptions about the constancy of underlying reflectivity and extraterrestrial solar irradiance. The 42-year time series of the deduced net solar irradiance at the level of MLO is shown in Figure 3.17 [*Dutton and Bodhaine*, 2001]. The maximum sustained solar radiative forcing from varying atmospheric transmission over Mauna Loa, determined from deduced net solar irradiance changes at 3.4 km above sea level (ASL), was less than –0.3 W m^{-2} over the last 40 years. In other words, the only linear trend that could have existed in net solar irradiance at the level of Mauna Loa but not have been detected would be between 0 W m^{-2} and –0.075 W m^{-2} per decade, thereby also

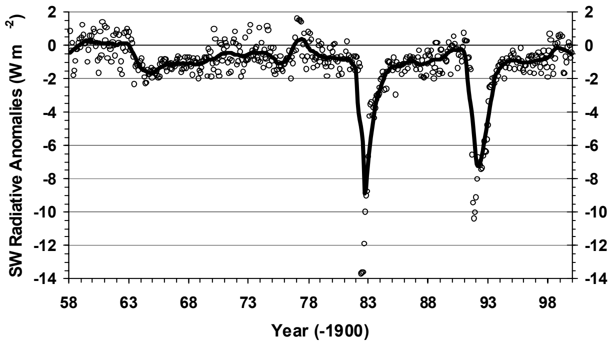

Fig. 3.17. Net solar irradiance variations at the height of Mauna Loa because of changes in atmospheric transmission over Mauna Loa.

eliminating the possibility of any positive trend. This work provides a longer history and more accurate determination of actual observed variations in radiative forcing as related to potential climate change than any other known directly observed radiation record.

Improvements in Diffuse Solar Irradiance Measurements

Total downwelling solar irradiance is the primary input component of the Earth's energy budget. One step in the improvement of the instantaneous surface-based solar irradiance measurements was the BSRN recommendation for using the combination of the separately measured direct and diffuse irradiance, which incorporates the highly accurate direct beam measurement capabilities developed over the past four decades and greatly reduces the cosine response error inherent in the single-instrument flat-plate receiver of the pyranometer. This method of measuring total solar irradiance led to improvements discussed by *Ohmura et al.* [1998], *Bush et al.* [1999], and *Michalsky et al.* [1999]. This recommendation has placed new requirements on the necessary documented accuracy of diffuse measurements. Although accuracy specifications for direct solar irradiance are rather easily determined, there are difficulties for the diffuse component because no reference standards exist. This has resulted in some recent modifications in the way in which STAR is making diffuse irradiance measurements, both in the type of instruments used and the adjustments for thermal offsets induced in certain diffuse pyranometers. The specifics of new diffuse solar measurements and adjustments to older data are given by *Dutton et al.* [2001]. With these changes, it is estimated that diffuse irradiance is currently measured to within about 5 W m^{-2}. This results in accuracies to within about 8 W m^{-2} for total solar irradiance when determined from the combined diffuse and direct measurements. STAR is involved in ongoing national and international efforts to promote the development of international reference standards and further improve the absolute accuracy of solar diffuse measurements.

Each CMDL BSRN site was also equipped to monitor diffuse sky radiation with a tracking-disk-shaded black and white pyranometer to augment the diffuse sky measurements made with single-black-detector-type pyranometers. The addition of pyranometers with black and white detectors enables more thorough monitoring of zero-offset effects. Solar trackers at each site were modified to enable installation of the additional shaded black and white detector pyranometers.

Thermal IR Irradiance Measurement Improvements

Although there have been substantial reductions in the uncertainty of thermal IR measurements in the past 10 years, from nearly ±30 W m^{-2} in the late 1980s to about ±5 W m^{-2} now (based on experiences in CMDL and elsewhere), there still appears to be room for further improvements and the potential for the establishment of a measurement reference standard. Over the past 2 years, STAR has become involved in the efforts of BSRN and the World Radiation Center (WRC) in Davos, Switzerland, to work toward these potential improvements. This work is through the establishment of new radiance measurement capabilities that rely on absolute, self-calibrating, sky-scanning instruments that could eventually determine a world reference group similar to that used to establish the World Radiometric Reference (WRR) for solar direct beam observations. CMDL, working with BSRN, helped organize and participated in the International Pyrgeometer and Absolute Sky-scanning Radiometer Comparisons (IPASRC-I and II), in the central United States during September 1998 and in the Arctic at Barrow during March 2001, respectively, where this process to establish such capabilities and reference standards began [*Philipona et al.*, 1998]. The results of the first of these comparisons and the operation of the sky scanner suggest that an absolute longwave irradiance measurement made routinely in the field can achieve the accuracy of close to ±1-2 W m^{-2} [*Philipona et al.*, 2001].